

# GAMMA-RAY BURSTS: CHALLENGES TO RELATIVISTIC ASTROPHYSICS

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Although they were discovered more than 25 years ago, gamma-ray bursts are still a mystery. Even their characteristic distance is highly uncertain. All that we can be confident about is that they involve compact objects and relativistic plasma. Current ideas and prospects are briefly reviewed. There are, fortunately, several feasible types of observation that could soon clarify the issues.

## 1 History

Astrophysics is a subject where the observers generally lead, and theorists follow behind. The topic of my talk is one where the lag is embarrassingly large. However, gamma-ray bursts raise issues which are certainly fascinating to everyone involved in relativistic astrophysics.

Even though the history of gamma-ray bursts dates back more than 25 years, we still know neither where nor what they are. The story started in the late 1960s, when American scientists at Los Alamos had developed a set of satellites aimed at detecting clandestine nuclear tests in space by the associated gamma-ray emission. Occasional flashes, lasting a few seconds, were indeed detected. It took several years before these were realised to be natural, rather than sinister phenomena, and in 1973 a paper was published by Klebesadel, Strong & Olson entitled *Observations of Gamma-ray Bursts of Cosmic Origin*. This classic paper reported 16 short bursts of photons in the energy range between 0.2 and 1.5 MeV, which had been observed during a three-year period using widely separated spacecraft. The burst durations ranged from less than 0.1 second up to about 30 seconds, but significant fine time-structure was observed within the longer bursts. The bursts evidently came neither from the Earth nor from the Sun, but little else was clear at that time.

It did not take long for the theorists to become enthusiastically engaged. At the Texas conference in December 1974, Ruderman (1975), gave a review of models and theories. He presented a long and exotic menu of alternatives that had already appeared in the literature, involving supernovae, neutron stars, flare stars, antimatter effects, relativistic dust, white holes, and some even more bizarre options. He noted also the tendency, still often apparent,

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for theorists to “strive strenuously to fit new phenomena into their chosen specialities”.

In the 1970s and 1980s, data accumulated on gamma-ray bursts, due to a number of satellites. Particular mention should be made of the contributions by Mazets and his colleagues in Leningrad. Also important were the extended observations made by the Pioneer Venus Orbiter (PVO). The number of detected bursts rose faster than the number of models – a further index of progress is that some of the conjectures reviewed by Ruderman were actually ruled out.

During that period, three classes of models were pursued: those in which the bursts were respectively in the Galactic Disc (at distances of a few hundred parsecs), in the halo (at distances of tens of kiloparsecs), and at cosmological distances. The characteristic energies of each burst, according to these three hypotheses, are respectively  $10^{37}$  ergs,  $10^{41}$  ergs, and  $10^{51}$  ergs. The most popular and widely-discussed option during the 1980s was that the bursts were relatively local, probably in our Galactic Disc, and due to magnetospheric phenomena or “glitches” on old neutron stars (defunct pulsars).

It was clear that there were two statistical clues which could in principle decide the location of gamma-ray bursts as soon as enough data had accumulated, and selection effects were understood. One was the number-versus-intensity of the events, which tells us whether they are uniformly distributed in Euclidean space, or whether we are in some sense seeing the edge of the distribution. The other is the degree of anisotropy.

There was already evidence that the counts of gamma-ray bursts were flatter than the classic Euclidean slope, since otherwise more faint bursts would have been detected by balloon experiments. This would not of course have been unexpected if the bursts were within the galaxy. However, the real surprise came with the launch, in April 1991, of the Compton Gamma Ray Observatory (GRO) satellite, whose Burst and Transient Source Experiment (BATSE) offered systematic all-sky coverage, with good sensitivity over the photon energy range 30 keV - 1.9 MeV. Data from BATSE have transformed the subject.

The most remarkable BATSE result is the unambiguous evidence that the bursts are highly isotropic over the sky. More than 1700 have now (December 1996) been recorded, and there is still no statistical evidence for any dipole or quadrupole anisotropy, nor for any two-point correlation (Briggs *et al.* 1997). The lack of any enhancement either towards the plane of the Galaxy, or towards the Galactic Centre, is a very severe constraint on the hypothesis that bursts come from the Galaxy. Note that they cannot be ultra-local objects within our galactic disc: this would naturally permit isotropy, but is ruled out by the flatness of the number counts. The “non-Euclidean” counts imply that

the surveys are probing to distances where the sources are, for some reason, thinning out; the problem is to account for this by a hypothesis that is also consistent with the isotropy.

The experiments on GRO have produced evidence on the spectra and time structure of events. (For a recent review, see Fishman (1995) and references cited therein.) Despite the large variety, there is little doubt that gamma-ray bursts are a well-defined class of objects, distinguished spectrally from phenomena such as X-ray bursters, and also from the so-called “soft gamma repeaters” which have substantially softer spectra. Within this class, there are some apparent correlations. For instance, the shorter bursts tend to be stronger and to have somewhat harder spectra; the histogram plotting burst durations may have two peaks; and the counts deviate most from the Euclidean slope for the bursts with harder spectra (Kouveliotou et al 1996).

The manifest isotropy has tilted the balance of opinion strongly towards a cosmological interpretation of the classical gamma-ray bursts. I will concentrate on discussing the challenge posed to theorists by that model. But I will then mention, more briefly, types of halo model that are compatible with the isotropy since these cannot yet be definitively deemed irrelevant. In conclusion, I will list some observations which might in the near future settle the issue, or at least reduce the current level of perplexity. This talk (and the present written version) is intended as a general overview. Fuller details, and more extensive references, can be found in the papers from the special session on gamma-ray bursts, elsewhere in these proceedings, or in Hartmann (1996).

## 2 Models for “Cosmological” Bursts

If the bursts are cosmological, then the sub-Euclidean counts imply that the typical burst has a redshift  $z$  of order 1. The precise redshift distribution depends on how much evolution there is in the population. The mean redshift would be less, for instance, if the burst rate increased with cosmic time. However, we can confidently say that all but the very nearest of the observed bursts must have redshifts of at least 0.2. Otherwise evolution would need to be implausibly steep to explain the non-Euclidean counts, and nearby superclusters would show up in the distribution over the sky. (Since the bursts exhibit such a wide variety of time-structures, it would be astonishing if, by any measure, they were anywhere near being standard candles. Obviously, detailed interpretations of the counts depend on the luminosity function.)

The event rate per unit volume is very low if we are sampling a population out to cosmological distances. It is of order  $10^{-5}$  per year per galaxy, in other words a thousand times less than the supernova rate in galaxies. The

required energy release then amounts to  $10^{51}$  ergs in a few seconds. (Both the estimates of the rates and of the energy per event would need to be adjusted in a straightforward way, of course, if the individual events were beamed in a small solid angle.)

### 3 “The trigger”

The total energy is not necessarily in itself a problem. After all, whenever a supernova goes off, the binding energy of a neutron star is released in a fraction of a second, and this amounts to  $10^{53}$  ergs, a hundred times what is needed for the burst. But in a supernova most of this energy goes to waste as neutrinos; moreover, any impulsive electromagnetic release would not escape promptly, but would be degraded by adiabatic expansion of the envelope before, much later, it could leak out. So is it possible for some rare events to occur where the energy release can escape promptly, rather than being surrounded by an extensive opaque envelope? The most widely favoured possibility is coalescence of binary neutron stars (see, for example, Narayan, Paczynski and Piran 1992). Systems such as the famous binary pulsar will eventually coalesce, when gravitational radiation drives them together. The final merger, leading probably to the production of a black hole, happens in a fraction of a second (though the swallowing or dispersal of all the debris may take somewhat longer). The calculated event rates for such phenomena – and perhaps also for the coalescence of binaries consisting of a neutron star and a black hole, rather than two neutron stars – are uncertain but are probably high enough to supply the requisite rates of bursts.

### 4 Fireball and gamma-ray emission

How can the energy be transformed into some kind of fireball after such a coalescence event? There seem to be two options. The first is that some of the energy released as neutrinos is reconverted, when the neutrinos collide outside the dense core where they were produced, into electron-positron pairs or photons. The rate of this process depends on the square of the neutrino luminosity, and those simulations that have so far been carried out yield rather pessimistic estimates for the efficiency (Ruffert *et al.* 1996). The second option is that strong magnetic fields directly convert the rotational energy of the system into a directed outflow. This latter option requires that the magnetic fields be amplified to strengths of order  $10^{15}$  Gauss. (Usov 1994; Thompson 1994)

The observed gamma rays seem to have a nonthermal spectrum. Moreover, they commonly extend to energies above 1 MeV, the pair production threshold in the rest frame. These facts together imply that the emitting region must be relativistically expanding. We draw this conclusion for two reasons. Firstly, if the region were indeed only a light second across or less, as would be implied by the observed rapid variability in the absence of relativistic effects, the total mass of baryons in the region would need to be below about  $10^{21}$  grams in order that the electrons associated with the baryons should not provide a large opacity: the rest mass energy of the baryons would need to be 10 orders of magnitude less than that of the radiation energy in the same volume. Not only is this a remarkably low figure, implying that only  $10^{-12}$  of the material from the compact objects is mixed up in the emitting region, but it would in any case imply a relativistic expansion. Quite apart from the baryon constraint, there is a second reason for invoking relativistic expansion. Larger source dimensions are required in order to avoid opacity due to photon-photon collisions (via  $\gamma + \gamma \rightarrow e^+ + e^-$ ).

If the emitting region is expanding relativistically, then for a given observed variation timescale the dimension  $R$  can be increased by  $\gamma^2$ . The opacity to electrons and pairs is then reduced by  $\gamma^4$ , and the threshold for pair production, in our frame, goes up by  $\sim \gamma$  from its “rest” value of  $\sim 1$  MeV. A high  $\gamma$  will of course only be attained if the baryon loading is sufficiently low, such that the ratio of total energy to rest mass energy is larger than  $\gamma$ . A variety of models have been discussed. Best-guess numbers are, for an energy of  $10^{51}$  ergs, a Lorentz factor  $\gamma$  in the range  $10^2$  to  $10^3$ , allowing the rapidly-variable emission to occur at radii in the range  $10^{14}$  to  $10^{16}$  cms. The entrained baryonic mass would need to be below  $10^{-6}M_\odot$  to allow these high relativistic expansion speeds.

Because the emitting region must be several powers of ten larger than the compact object that acts as “trigger”, there is a further physical requirement: the original energy – whether envisaged as an instantaneous fireball or as a short-lived quasi-steady wind – would, during expansion, be transformed into bulk kinetic energy (with associated internal cooling). It must be re-randomised and efficiently radiated as gamma rays: this requires relativistic shocks. Impact on an external medium (or an intense external radiation field) would randomise half of the initial energy merely by reducing the expansion Lorentz factor by a factor of 2. Alternatively, there may be internal shocks within the outflow: for instance, if the Lorentz factor in an outflowing wind varied by a factor more than 2, then the shocks that developed when fast material overtakes slower material would be internally relativistic (Piran 1997 and references cited therein).

In the case of expansion into an external medium, the energy would be rethermalised after sweeping up external matter with rest mass  $E/c^2\gamma^2$  (Rees & Mészáros 1992; Mészáros & Rees 1993). For  $E = 10^{51}$  ergs and  $\gamma = 10^3$ , only  $10^{-9}M_\odot$  of external matter need be swept up. In an unsteady wind, if  $\gamma$  were to vary on a timescale  $\delta t$ , internal shocks would develop at a distance  $\gamma^2 c\delta t$ , and randomise most of the energy (eg Rees & Mészáros 1994). For instance, if  $\gamma$  ranged between 500 and 2000, on a timescale of  $\delta t$  second, internal shocks with Lorentz factors  $\sim 2$  (measured in the frame of the mean  $\gamma \simeq 1000$  outflow) would lead to efficient dissipation at  $3 \times 10^{16}\delta t$  cms.

Another important consequence of relativistic outflow is that only material moving within an angle  $\gamma^{-1}$  of the line of sight contributes to what we observe. Observations cannot therefore tell us if bursts are highly beamed. Transverse pressure gradients are only effective on angles below  $\gamma^{-1}$ , so material ejected in widely differing directions behaves quite independently. There are already a variety of models in the literature discussing the radiation from shocks in expanding fireballs and relativistic winds (see Piran 1997 for a recent review). The parameters are uncertain, and the relevant physics, involving for instance the coupling between electrons and ions in relativistic shocks, is not sufficiently well developed to allow accurate modelling of the radiation (see, for instance, Gallant *et al.* 1992).

So how is the original energy channelled from the central object into the outflowing fireball or wind. Recent calculations by Ruffert *et al.*, 1996, suggest problems with releasing neutrino energy efficiently enough, and on a short enough timescale, to allow production of a fireball. The options involving *magnetic* energy (cf Narayan, Paczynski & Piran 1992) are rather less quantitative, but I still believe they are more promising. As discussed by Usov, (1994), and Thompson (1994), a millisecond pulsar with a  $\sim 10^{15}$  Gauss field would be slowed down in 1 second, its spin energy being dumped in a pair-dominated relativistic wind. As these authors and others have discussed, internal processes in such a wind could explain gamma rays with the observed spectrum and variability characteristics.

## 5 A “best buy” model

My personal favourite model (cf Meszaros and Rees 1997b) involves the toroidal debris from a disrupted neutron star orbiting around a black hole. If this debris contains a strong magnetic field, amplified perhaps by differential rotation, then an axial magnetically-dominated wind may be generated along the rotation axis, perpendicular to the plane of the torus. The advantage of this geometry is that it seems to offer the best chance of preventing baryon

contamination, because the baryonic material would be precluded by angular momentum from getting near the axis without first falling into the black hole or being on a positive-energy trajectory.

Such a configuration could arise from capture of a neutron star by a black hole of less than  $5M_{\odot}$ , this mass limit being required because otherwise the neutron star would be swallowed before disruption. Alternatively, it could be the outcome of the merger of two neutron stars, where most of the mass collapses to a black hole, leaving some fraction of the original material in orbit around it. (cf Ruffert *et al.* 1996; Jaroszynski 1996)

The available energy in this model is the kinetic or gravitational energy of the neutron-star debris left behind in the torus, plus the spin energy of the hole itself (which, being the outcome of binary coalescence, is almost guaranteed to have a high angular momentum). Near the axis, we would expect maximal dissipation (from fields threading the hole or anchored in the torus) but minimum baryonic loading. The Lorentz factor would therefore be largest along the axis. Indeed, a narrow channel, essentially free of baryons, may carry a Poynting-dominated outflow, energised by the hole via the Blandford-Znajek process.

Along any given line of sight, the time-structure would be determined partly by the advance of jet material into the external medium, but probably even more by internal shocks within the jet, which themselves depend on the evolution and instabilities of the torus, from its formation to its eventual swallowing or dispersal. Even if the bursts were caused by a completely standardised set of objects, their appearance would be likely to depend drastically on orientation relative to the line of sight. Other phenomena as yet undiscovered – for instance some new class of X-ray or optical transient – may be attributable to gamma-burst sources viewed from oblique orientations.

## 6 Physics of the emission mechanism

We are a long way from a convincing model for what triggers gamma-ray bursts: coalescing compact binaries seem likely to be implicated, but we should remain open-minded to more exotic options. A precise description of the dynamics, along with the baryon content, magnetic field, and Lorentz factor of the outflow, might allow us to predict the gross time-structure. But even then we could not predict the intensity or spectrum of the gamma rays – still less answer key questions about the emission in other wavebands – without also having an adequate theory for particle acceleration in relativistic shocks. We need the answers to the following poorly-understood questions:

- (i) Do relativistic shocks yield particle spectra that obey power laws? This

is in itself uncertain: the answer probably depends on the ion/positron ratio, and on the relative orientation of the shock front and the magnetic field (e.g. Gallant *et al.* 1992).

(ii) In ion-electron plasmas, what fraction of the energy goes into the electrons?

(iii) Even if the shocked particles establish a power law, there must be a low-energy break in the spectrum at an energy that is in itself relativistic. But will this energy, for the electrons, be  $\Gamma_s m_e c^2$ , or  $\Gamma_s m_p c^2$  (or even, if the positive charges are heavy ions like Fe,  $\Gamma_s m_{\text{Fe}} c^2$ ?

(iv) Can ions be accelerated up to the theoretical maximum where the gyroradius becomes the scale of the system? If so, the burst events could be the origin of the highest energy cosmic rays (an interesting possibility addressed by other speakers at this conference)

(v) Do magnetic fields get amplified in shocks? This is relevant to the magnetic field in the swept-up external matter outside the contact discontinuity, and determines how sharp the external shock actually is (cf Mitra 1996)

(vi) Can radio emission be generated by a coherent process? If not, the usual surface brightness constraint implies that there would be little chance of detecting a radio “afterglow”.

These questions, crucial for gamma ray bursts, are also relevant to other phenomena. For example, Lorentz factors of at least 10 (and probably electron-positron plasmas) exist in the compact components of strong extragalactic radio sources probed by VLBI.

If one is prepared to parametrise the uncertainties implicit in the above questions, predictions can be made of how the spectrum would evolve during a burst with simple time-structure. (eg Meszaros *et al.* 1994, Tavani 1996, Meszaros and Rees 1997). For a wide range of parameters, the associated X-rays would be above the threshold of small omnidirectional detectors such as those developed for the High Energy Transient Explorer (HETE) It was therefore a real setback to the subject – particularly to the prospect of using concurrent X-ray or UV emission to pinpoint the burst locations more accurately – when HETE failed to go properly into orbit.

After the main emission is over, the fireball material would continue to expand, with steadily-falling Lorentz factor, into the external medium. Associated optical emission may persist for hours or even days. This is long enough to allow an initial detection with BACODINE to be followed up by raster scans with a 1 m telescope, that could detect even emission down to 15th magnitude.



## 7 “Extended Halo” Models

In the interests of balance, I would like to make a few remarks about the alternative idea that the bursts are not from cosmological distances, but instead come from within our own galaxy. Classical gamma-ray bursts could be isotropic enough to be consistent with the BATSE data if they came from neutron stars ejected from our Galactic Disc at more than  $700 \text{ km s}^{-1}$ , which remained active, bursting sporadically, for long enough to allow them to reach distances of at least 100 kiloparsecs. They may either escape from the galaxy, or be on very extended bound orbits. These high velocity objects could be a special subset of pulsars. The typical velocities of the pulsars sampled in surveys may be as high as  $400 \text{ km/sec}$  (Lyne and Lorimer 1994, J. Taylor, these proceedings). Moreover, those that formed with higher kick velocities and/or with strong magnetic fields (and therefore short lifetimes) are under-represented in surveys; we cannot exclude the possibility that a high fraction of newly-formed pulsars are of such types. If we conservatively suppose that they are only a few percent of all pulsars, and form in our Galactic Disc at a rate of about 1 per thousand years, then each must produce  $10^6$  bursts, of typical energy  $10^{41}$  ergs. (If the relevant objects formed at a rate of one per 100 years, the requirements placed on each would be ten times more modest.) Repetition would not necessarily be expected, since each neutron star could in principle continue bursting at a slow rate for more than a billion years. However, if the bursts came in groups, rather than being independent poissonian events, repetition would not be impossible.

## 8 Fitting the isotropy

Podsiadlowski has done detailed calculations of whether such a population can provide an isotropic distribution. He shows this is indeed possible for long-lived bursters whose orbits take them out beyond 100 kiloparsecs. An important feature of such orbits is that, because the galactic halo potential is not spherical (and may indeed be rather irregular at such large distances) objects do not conserve their angular momentum and therefore, even if they started off near the centre of our Galaxy, they need not return so close to the centre in later orbits. This effect helps to ensure greater isotropy. Another possibility, favoured by Lamb (1995), is that the typical objects have velocities above a thousand kilometres per second, and are escaping the Galaxy completely. In this case, the best fit is obtained if the bursts do not start until after a delay of around  $10^7$  years, by which time all neutron stars have reached distances of 30 kiloparsecs or more.

I think it is fair to say that such models need to be carefully tuned in order to fit the existing isotropy data, but that, though perhaps unappealing, they cannot be ruled out. The constraints on orbital parameters would be eased in alternative schemes where the neutron stars *formed* far out in the halo (being perhaps, as Woosley (1993) has discussed, relics of an early population of halo stars) rather than being ejected from the disc.

## 9 Mechanisms for halo bursts

If a “halo” model is to be taken seriously, there must be an acceptable mechanism for producing the succession of  $10^{41}$  erg bursts, spread over a very long timescale. Two options have been proposed (Podsiadlowski, Rees & Ruderman 1995).

The first possibility is that the relevant subset of neutron stars start off with a super-strong ( $\gtrsim 10^{15}$  Gauss) magnetic field. This field, penetrating the core of the neutron star, would gradually rise towards the surface through buoyancy effects, thereby causing stress in the crust. The timescale for the buoyancy is estimated to be at least  $10^6$  years. Acceptable models require that it be  $\gtrsim 10^9$  years. The total stored energy is  $\sim 10^{47}(B/10^{15}G)$  ergs. The energy depends linearly on  $B$ , rather than quadratically, because the field in the core is concentrated into tubes where its strength has a standard value of  $\sim 3 \times 10^{15}G$ .

The crust gets stretched as the field drifts outwards. The units in which energy is released depend on how much stress can build up in the crust, and what fraction is released when the crust cracks. This is a complicated problem in asteroseismology. However, a release of  $10^{41}$  ergs per event is plausible, in which case the total stored magnetic energy would be sufficient to supply the requisite  $10^6$  events.

The second very different option for triggering halo bursts involves asteroidal impacts on to a neutron star. Each event requires, on energetic grounds, the impact of  $10^{21}$  grams. The main problem with this idea is that such asteroidal or cometary bodies would be tidally disrupted too far out to give a sudden enough event. A possible solution is that the debris from the disrupted body squashes down the magnetic field, which then rebounds, generating high electric fields and thereby a pair cascade. Alternatively, the debris may form a disc which accumulates before triggering a sudden electromagnetic release when it couples its rotation to that of the neutron star.

The total impacting mass, to get enough bursts per star, must be  $10^{27}$  grams. It is not impossible (especially now we know that planetary systems can exist around pulsars) that a neutron star could carry with it  $\gtrsim 10^{27}$  gm of

asteroidal debris. However, a larger reservoir, plus at least one large planet, is needed in order for enough of these planetesimals to be perturbed on to near radial orbits. We know that at least one pulsar has a planetary system. This fact, plus the evidence that even typical pulsars may have velocities of  $400 \text{ km s}^{-1}$ , suggests that models of this kind should not be dismissed. Whatever the bursts turn out to be, the primary trigger, and the efficient conversion of its energy into gamma rays, involve physical conditions that are extreme and unfamiliar.

## 10 How can we settle the debate?

There is no convincing and fully worked out model for the bursts on either the halo or the cosmological hypothesis. Neither option, however, seems to violate any cherished beliefs in physics or relativistic astrophysics. The issue is one of plausibility, and how one weighs different lines of evidence. The isotropy would be a natural consequence of the cosmological hypothesis. But the level of isotropy so far revealed by BATSE, which restricts any dipole or quadrupole anisotropy below the few per cent level and shows no evidence for clumping on smaller scales, could be accommodated in a halo hypothesis if high speed neutron stars were implicated.

In April 1995, the 75th anniversary of the Shapley/Curtis debate, there was an interesting debate in Washington on the location of gamma-ray bursts – a current issue offering some amusing parallels to the earlier controversy concerning the distances of the nebulae. The two main protagonists were Don Lamb and Bohdan Paczynski (a written version of the argument appears in Lamb (1995) and Paczynski (1995)). I had the privilege of acting as the moderator in this debate, perhaps because I was one of the few people who had not already taken a firm stance on one side of the issue or the other. There was an agreement among all participants that the issue would be settled only by more data. Indeed, there was a broad consensus on some particular tests that could be crucial, or at least highly suggestive. Among these might be the following.

Most valuable of all would be a firm identification of a burster with some other class of object. The stumbling block here is the poor positional accuracy of most gamma-ray detectors. BATSE itself has error circles of 1 or 2 degrees for the brightest bursts, and more than 5 degrees for the fainter ones. However, the locations of some bursts have been pinned down with a precision of minutes of arc or better by triangulation experiments involving deep space probes; this technique utilises the rapid time structure, which, when recorded and timed by detectors separated by 10 light minutes or more, allows accurate

positioning. There is still no firm identification of any classical gamma-ray burst, though there are tantalising indications that some of the brighter bursts may be correlated with galaxies or clusters of galaxies, whose distances are not inconsistent with what is expected on the cosmological hypothesis. (It is disappointing, incidentally, that the failure of the recent Mars probe, which would have carried a small gamma-ray detector, means that we now lack the requisite deep-space network for obtaining accurate “triangulation”.)

Even though the gamma-ray positional information is poor, one might be able to pin down the position of the sources more accurately if they displayed concurrent transient emission in some other waveband. Various projects have been undertaken in the optical and radio band. Ground-based observers can be notified of a BATSE event within a few seconds; a small telescope can then be rapidly slewed to seek an optical counterpart within less than a minute. No such counterparts have been detected, nor have radio searches yet yielded positional or timing coincidences. The likely strength of gamma-ray bursts in the optical or radio band is uncertain and highly model-dependent. Indeed, any detection in these wavebands would have the bonus that it would help to narrow down the range of possible models and emission mechanisms. However, most theories predict that there should be substantial spectral extension from gamma-rays down towards the X-rays, so it would seem less of a gamble to seek X-ray counterparts.

If the bursts have a local rather than cosmological origin, then, at some level, anisotropies over the sky would be bound to show up. A particularly crucial test would be feasible if bursts more than ten times fainter than those recorded by BATSE could be detected. It would then, according to the halo hypothesis, be feasible to detect bursts from the halo of Andromeda, and there should be a definite excess of weak events from that direction (Bulik & Lamb 1997, Ruszkowski & Wijers 1997). The lack of such a trend would severely embarrass halo models. A specific proposal has been made to look at a 10 degree field around Andromeda with 20 times the sensitivity of BATSE. But X-ray detectors are more readily available and more sensitive. For this reason, and also because the x-ray emission from bursts seems stronger than a straight extrapolation of the gamma-ray spectrum suggests (Preece *et al.* 1996), the best prospects for testing the halo model might be from long-duration observations of Andromeda and other nearby galaxies.

The cosmological interpretation of bursts would be confirmed, as Paczynski (1986) first pointed out, if there were evidence of gravitational lensing by an intervening galaxy. If a suitable galaxy lay along the line of sight to a cosmologically distant burst, radiation would reach us by two or more different paths, whose light travel times would differ typically by weeks or months. We

would therefore detect two bursts from the same direction. Even though the positions could not be pinned down accurately, the elaborate time structure of each burst is highly distinctive, and if two bursts with identical “fingerprints” were detected from within the same error circle, this would be compelling evidence that they were actually separate gravitationally-lensed images of the same burst. (As a technical point, it should be noted that microlensing by stars or substellar objects would only introduce differences on millisecond timescales between the two burst profiles (Williams and Wijers 1997), and therefore would not vitiate this possibility.)

Unfortunately, the probability that a galaxy lies along a random line of sight to a high redshift object is below one per cent, the exact value depending of course on the presumed redshift of the burst. Moreover, because BATSE can only observe a given direction in the sky for about 40 per cent of the time it is more likely than not that, if a lensed event occurred, the recurrence would be missed because it would occur during dead time. Taking these effects into account, it is rather marginal whether we would expect BATSE to detect a single instance of this lensing before it dies, even if the bursts indeed come from cosmological distances. However, if we were lucky, such a double burst could clinch the cosmological interpretation.

A further issue which has figured strongly in the debate on the location of gamma-ray bursts concerns the existence or otherwise of spectral features attributable to cyclotron lines. This is a technical controversy which I will not enter here. However, its relevance lies in the fact that halo models involve neutron stars, where the magnetic fields are expected to be in the range such that cyclotron lines should be in the hard X-ray band. On the other hand, the fields in the emitting regions of cosmological fireballs or relativistic winds would not, even when relativistic effects are taken into account, give rise to such features.

The controversies in the Shapley-Curtis debate were settled within a few years. Our knowledge of extragalactic astronomy thereby made a forward leap, and astronomers moved on to address more detailed issues. I’m enough of an optimist to believe that it will be only a few years before we know where and perhaps even what, the gamma-bursters are. Even if this optimism is misplaced, I am completely sure that these mysterious phenomena will serve as a continuing challenge and stimulus to theorists, and will remain high the agenda of future Texas Conferences.

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